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GYROKINETIC AND GLOBAL FLUID SIMULATIONS OF TOKAMAK MICROTURBULENCE AND TRANSPORT

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Abstract

Results are presented from the first systematic nonlinear kinetic simulation study of the scalings and parameter dependences of toroidal ion-temperature-gradient (ITG) turbulence and transport, and from the first such study that includes sheared toroidal flows. Key results include the observation of clear gyroBohm scaling of the turbulent transport and of a surprisingly weak dependence of the transport on toroidal flow shear. Based on the simulation results, a parameterization of the transport is given that includes the dependence on all of the relevant physical parameters. The transition from local to nonlocal transport as a function of the profile scale length has been investigated using two-dimensional global fluid simulations of dissipative drift-wave turbulence. Local gyroBohm scaling is observed, except at very short profile scale lengths.

DISCLAIMERS

GYROKINETIC SIMULATIONS OF ITG TURBULENCE

Transport in tokamaks is observed to be anomalous for one or more of the heat, particles and momentum. Efforts to understand this transport generally involve some compromise between tractability and realism transport. The development of various advanced algorithm components has allowed nonlinear toroidal gyrokinetic simulations to reach a level where practical simulations of turbulent phenomena for realistic parameter values are possible. Results from such simulations of ion-temperature-gradient-driven (ITG) turbulence are reported here.

The physical model used consists of a single nonlinear gyrokinetic ion species, with equilibrium temperature, density, and toroidal velocity gradients, and adiabatic electrons. The electron response to the flux-surface-averaged potential is taken to be zero [1]. The model is fully toroidal, incorporating the magnetic drifts and trapped ions. The resulting equations are solved using the partially linearized δf particle method [2].

The field quantities in the code are defined on a quasiballooning-coordinate grid as described in Ref. [4]. This allows a smooth implementation of the toroidal periodicity condition across the parallel boundary and has optimal resolution. The simulation domain used is a flux tube of small perpendicular extent, but which spans one or more poloidal circuits in the parallel direction. The parallel periodicity condition applied to the flux tube ends corresponds to the true physical tokamak toroidal periodicity condition.

Quasilinear relaxation [1] is avoided by using a generalization of Kotschenreuther's twist-shift radial periodicity condition [3]. This generalization works even in the presence of sheared toroidal or perpendicular flows by allowing the radial boundaries to move relative to each other with a speed equal to the difference between the external flow speed at the two boundaries. This periodicity condition gives our code a unique ability to simulate ITG turbulence in the presence of controlled sheared flows.

These methods allow simulations for realistic tokamak parameter values on the order of an hour of C-90 wallclock time.

Many simulation runs have been completed in what is the first systematic kinetic nonlinear simulation study of the scalings and parameter dependences of toroidal ITG turbulence and transport. The parameter values have been varied one at a time from a base simulation case which represents conditions in a TFTR L-mode discharge at a minor radius $r = 0.5a$, where a is the minor radius of the last closed flux surface. These parameters are $\eta_{\rm i} \equiv L_{\rm n}/L_{\rm T} = 4$, where $L_{\rm T}$ is the ion temperature scale length and $L_{\rm n}$ the density scale length, magnetic safety factor $q = 2.4$, $s \equiv (r/q)dq/dr = 1.5$, where r is the minor radius, $\epsilon_T \equiv L_T/R_0 = 0.1$, where R_0 is the major radius at the minor axis, and $\epsilon_B \equiv r/R_0 = 0.21$.

Convergence has been checked and found to be adequate respect to particle number, grid and particle sizes in all three directions, and with respect to the number of poloidal circuits traversed by the flux tube.

Figure 1 shows that for sufficiently large box sizes, which are shorter than typical profile scale lengths, the thermal diffusivity normalized to $\chi_{\rm GB} \equiv \rho_{\rm s}^2 c_{\rm s}/L_{\rm T}$, where $\rho_{\rm s}$ and $c_{\rm s}$ are respectively a mean ion gyroradius and thermal velocity at the electron temperature, becomes independent of the box size. The transport therefore has a clear gyroBohm scaling. Self-generated flows regulate the turbulence levels and transport rates. For the base-case parameter set, zeroing out the self-generated flows gives a clean saturated state with $\chi_{\rm i} \simeq 3\chi_{\rm GB}$.

A parameterization of ion thermal diffusivity has been obtained from many simulation runs, varying parameters about the base case parameter set:

$$\chi_{\rm i} \simeq (6-8)\frac{\rho_{\rm s}^2 c_{\rm s}}{R_0}\hat{\chi}\left(q, \eta_{\rm i}, \frac{L_{\rm s}}{L_{\rm T}}, \frac{T_{\rm e}}{T_{\rm i}}, \epsilon_T, \epsilon_B, \frac{V_\zeta' L_{\rm T}}{c_{\rm s}}\right), \tag{1}$$

where $L_{\rm s} = qR_0/s$ is the magnetic shear length, $T_{\rm e}$ and $T_{\rm i}$ are the electron and ion temperatures, and V_ζ' is the *toroidal* velocity shear. The dependence of $\hat{\chi}$ on each of q, $\eta_{\rm i}$, ϵ_B, and $T_{\rm e}/T_{\rm i}$, with the other parameters set at the base-case values, is shown in Fig. 2. The ϵ_T dependence of $\hat{\chi}$ is weak for $0.04 \leq \epsilon_T \leq 0.2$.

This result is about a factor of 2 lower than the experimental value at the $r/a = 0.5$ flux surface of a sample TFTR L-mode discharge, and has an overall decrease in the transport as a function of minor radius, which is opposite to that seen in experiments. The thermal flux increases very little as $\eta_{\rm i} \to \infty$, i.e., the parameters are far from marginal stability. Thus, marginal-stability argument cannot account for the discrepancy. If mechanisms can be found that *increase* the over all transport rates, then a marginal-stability argument could account for the differences. Candidate mechanisms include trapped electrons and additional poloidal flow damping mechanisms.

This is the first simulation study of toroidal ITG turbulence in the presence of sheared toroidal flows that does not have an artificial radial boundary or radial discontinuity in the flow profile. Toroidal flow shear is an important ingredient in the DIII-D VH mode [5]. Surprisingly, for $V_\zeta' L_{\rm T}/c_{\rm s} = 1.15$ and 2.3, with the other parameters as for the base-case, $\hat{\chi}$ is hardly changed from the $V_\zeta' = 0$ value. The parallel component of the flow shear is strongly destabilizing since, for these values of the toroidal flow shear, the perpendicular component of the flow shear by itself completely stabilizes all of the modes present in our simulations. The toroidal momentum diffusivity is found to be slightly larger than the thermal diffusivity.

We have derived and implemented a set of nonlinear quasiballooning-coordinate gyrokinetic equations for realistic noncircular cross-section equilibria, extending an existing linear ballooning-coordinate formulation which was used in linear gyrokinetic simulations by Hua, Xu, and Fowler [6]. This will be added to the sheared-toroidal flow capability to study the toroidal spin up observed in the VH mode. Work is also underway to include trapped electron effects, nonlocal effects, and collisions in the code.

GLOBAL FLUID SIMULATIONS OF DISSIPATIVE DRIFT-WAVE TURBULENCE

A $2d(x, y)$ fluid code has been developed in order to explore non-local dissipative drift-wave turbulence [5], anomalous transport, and any transitions between local gyroBohm and nonlocal transport. The simulation consists of a set of fluid equations (in the electrostatic limit) for the vorticity $\nabla_\perp^2\phi$, and the density n in a shearless plasma slab. In order to obtain steady state turbulence, we force the y-averaged density fluctuation $<n>$ to be zero in simulations, thus avoiding the difficulty of choosing proper sources and sinks in turbulence simulation codes.

If $L_n \gg L_c$, where L_n is the density scale length, L_c is the turbulence correlation length, the results agree with "local" turbulence simulations [6]. However, for $L_n \sim L_c$, "local" turbulence codes are found to overestimate the flux. For a family of hyperbolic tangent background density profiles, $n_0(x) = n_m - n_1 \tanh(2x - L_x)/2\Delta_n)$ with $n_1 < 0.5n_m$, we have demonstrated that the non-locality of the turbulence leads to a transition from local Gyro-Bohm $[D^{local} \simeq 7.6(T_e/eB)(\rho_s/L_n(x))(\alpha^{lc}(x)/0.01)^{-1/3}]$ where $\alpha^{lc}(x) = \alpha(x)/\kappa(x) < 1$, to nonlocal Gyro-Bohm transport scaling $[D^{nonlocal} \simeq 7.6(T_e/eB)(n_1\rho_s/n_m\Delta_n)(\alpha^{nlc}/0.01)^{-1/3}$ $(\Delta_n/40\rho_s)^{2/5}$ for $\alpha^{nlc}(x) = \alpha/\kappa_{max} < 1$, $\kappa(x) = \rho_s/L_n(x)$ and $\alpha = k_{||}^2\chi_e/\Omega_i]$. The transition to non-local transport with non-local gyro-Bohm scaling is observed at very short profile scales, less than roughly $10\rho_s$ where ρ_s is the mean ion gyroradius at the electron temperature. The key factor in non-locality of the dissipative drift-wave turbulence in the shearless slab geometry is the adiabaticity-layer thickness (or the smallest equilibrium scale length, whichever is comparable to the radial correlation length of the turbulence). When the non-local effects play an important role, we observe that the profiles of turbulence flux and the root-mean-square fluctuation amplitudes are broader than the predictions of local simulations and the peak values are smaller. The physical reason is that as the eddy size is large compared with the adiabaticity-layer thickness, the averaged parallel damping $<\alpha^{lc}>$ is increased, thus the turbulence gets suppressed.

In the local analysis, the usual assumption is that the effect of density profile on the polarization drift is small $\{(m_ic^2/eB^2)\nabla_\perp \cdot [n(x)d\nabla_\perp\phi/dt] \simeq [n(x)m_ic^2/eB^2]\nabla_\perp \cdot (d\nabla_\perp\phi/dt)$, and $\nabla_\perp n(x) \cdot (\nabla_\perp\phi/dt) \ll \nabla_\perp \cdot [n(x)d\nabla_\perp\phi/dt]\}$. However, in the wave propagation theory, this term is a key factor in the amplification of the wave amplitudes as the waves propagate in space [7]. We have implemented this term in the fluid code to explore wave propagation phenomena for dissipative drift-wave turbulence. In the hydrodynamic limit, we found that for $L_n \gg L_c$, the $\nabla_\perp n(x) \cdot (\nabla_\perp\phi/dt)$ term makes a small contribution and the results agree with the usual "local" turbulence simulations. In the the adiabatic limit, we also have not seen any evidence of the enhancement of the edge turbulence as the wave propagation theory predicts.

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Figures

Fig. 1. Dependence of the normalized thermal diffusivity on the perpendicular box size, $\eta_{\rm i}$, and s. The physical parameters are as for the base case with the exception of the given parameter. The $L_z = 4\pi qR$ case refers to a run in which the simulation flux tube made two poloidal circuits. The perpendicular box size variations have the same box sizes in the two perpendicular directions and were done at fixed particle density.

Fig. 2. Dependences of $\hat{\chi}$ as defined in Eq.(1) diffusivity on q, $\eta_{\rm i}$, ϵ_B, and $T_{\rm e}/T_{\rm i}$. On each of the plots, only the selected parameter is varied. All other parameters are at the base-case values.

Figures:

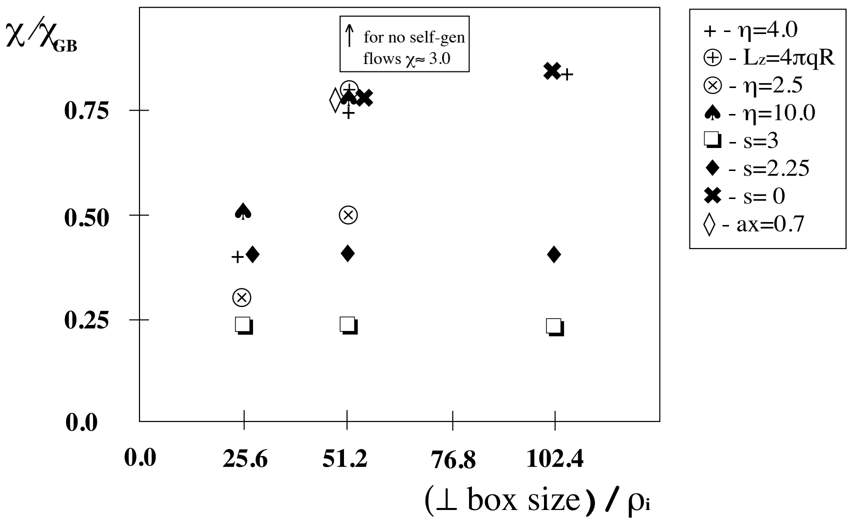

Figure 1

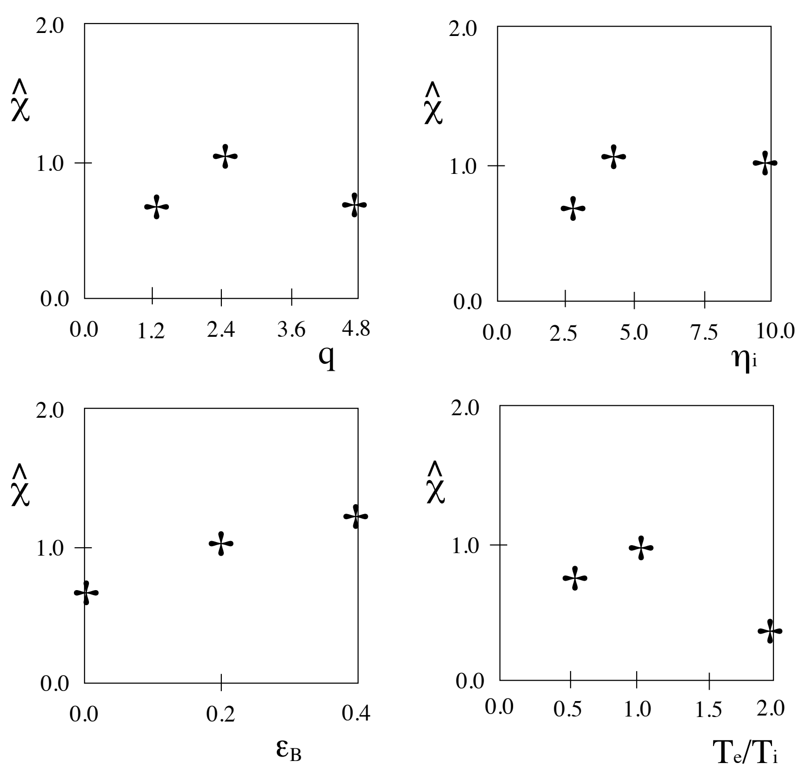

Figure 2